TITLE: AMPLIFIER CIRCUITS AND THEIR USE IN RADIO FREQUENCY TRANSMITTERS

FIELD OF THE INVENTION

The present invention relates to amplifier circuits and their use in RF (radio frequency) circuits such as transmitters, especially RF communications transmitters. In particular, it relates it relates to RF power amplifier circuits for use in such RF transmitter or transceiver units.

BACKGROUND OF THE INVENTION

Many RF generators such as those used in RF transmitters include power amplifier circuits. Such circuits may for example be employed in a communications transmitter to amplify a modulated RF carrier signal for external transmission by an associated radiating device such as an RF antenna. Such circuits are often required to have a substantial linearity of response providing an output which is a linear function of the input. Circuits operating in a class A and to a lesser extent in a class AB configuration are widely employed to provide linearity. However, such circuits are inefficient and consequently waste relatively large amounts of input power, especially in high power output applications. Amplifier circuits operating in a class C configuration may alternatively be used as power amplifiers. The class C configuration provides an output signal which is approximately in the form of a square waveform produced from a sinusoidal RF

input. Such amplifier circuits are of better efficiency than class A and AB circuits but unfortunately are highly non-linear. Class C amplifier circuits are not therefore used commercially in modern communications applications requiring complex linear modulation forms.

SUMMARY OF THE PRESENT INVENTION

According to the present invention in a first aspect there is provided an RF amplifier circuit comprising an RF amplifying device having a first input terminal, a second input terminal and an output terminal, means for applying to the first input terminal an input RF signal I to be amplified, means for generating and applying to the second input terminal a threshold signal T, and the amplifying device being operable to produce at the output terminal an output signal O which has a high finite value providing a Boolean '1' value when the instantaneous value of the amplitude of I is greater than T and a low finite value providing a Boolean '0' value when the instantaneous value of the amplitude of I is less than T, wherein the threshold signal T is dynamically varied in a manner adapted to linearise the relationship in at least part of its range between the amplitude of the output signal O and the amplitude of the input signal I.

Preferably, the amplifying device has a bandwidth of at least five times, preferably at least ten times, greater than the mean operating frequency of the signal which it is operable to amplify.

The threshold signal T may be a variable signal which

may be combined with the input signal I at the amplifying device as appropriate to give in combination a linear response as illustrated in more detail later. Alternatively, the threshold signal T may be applied as a variable bias signal to the amplifying device.

The threshold signal T may in operation be dynamically varied as a function of the input signal I, e.g. by sampling the input signal I prior to application to the amplifying device. The means for applying the threshold signal T may in this case comprise a feed forward loop which includes as the means for generating the threshold signal T means for generating a signal derived at least in part from the sampled input signal I.

Alternatively, or in addition, the threshold signal T may in operation be dynamically varied as a function of the output signal O, e.g. by sampling the output signal O produced by the amplifying device, optionally after further processing, e.g. filtering. The means for applying the threshold signal T may in this case comprise a feedback loop which includes as the means for generating the threshold signal T means for generating a signal derived at least in part from the sampled output signal O.

Where the threshold signal T is derived from the input signal I and/or the output signal O it may be provided by sampling the relevant signal and deriving as the threshold signal T or a component thereof a signal which is related to the envelope of the monitored signal. For example, the threshold signal T may be derived from a profile of the peak amplitude or of the root mean square amplitude of the varying monitored signal.

In a further alternative embodiment of the invention, the threshold signal T may be generated in an arrangement operable as follows. Variations in amplitude of the input signal I may result from the application of a modulation signal applied in a modulator to an RF carrier signal to form the input signal I. The modulation signal may be generated in the modulator in a known manner by converting input information to be communicated, e.g. digital information produced as an output from a digital signal processor, into the required modulations. The modulation signal may for example comprise digital phase shift modulations of the carrier signal. The phase shift modulations may be applied for example in a known DQPSK (differential quadrature phase shift keying) procedure. The threshold signal T may be a signal derived from the modulation information or the information, e.g. digital (including bidigital) information, to be converted into the modulation signal. The threshold signal T may therefore be derived from an output of a digital signal processor which also produces an output for application to a modulator.

The threshold signal T may have an amplitude profile calculated to correspond to the amplitude profile of the input signal I by an appropriate mathematical operation applied to the modulation signal or of the information employed to produce the modulation signal, e.g. from a digital signal processor. The amplitude profile of the input signal I as a function of the applied modulation signal or information, e.g. digital information, employed to produce it, can be calculated since the amplitude profile resulting from a given modulation signal is in general a known function. Alternatively, or in addition,

training measurements, e.g. using a neural network function, can be made of the input amplitude as a function of the applied modulation information or digital information converted into modulation information.

In a transceiver arrangement, the modulated signal generated in the manner described above may initially be a baseband frequency signal which is converted to RF by an upconverter to produce the input signal I. The calculated amplitude function in this case resulting from a given modulation signal will take into account the upconversion step.

The application of a mathematical operation may be carried out by a device referred to herein as an operator. As is known in the art of control design, the mathematical operation or function applied by an operator to produce an output signal from a given input signal applied to the operator is known as a transfer function. In the above embodiments of the invention, the operator used in each case is selected to apply a particular suitable transfer function to a particular input signal I to a produce a particular threshold signal T, e.g. as illustrated further later.

Devices which may be used to provide such an operator are known per se. In general, such a device may include a signal processor, e.g. digital signal processor, which carries out the transfer function. The operator may also include (i) a signal peak monitor which measures the value of the peak of a signal being sampled and produces a peak envelope signal, (ii) an A to D (analogue to digital) converter which digitises the peak envelope signal for application to the signal processor and a D

to A (digital to analogue) converter which converts the digitally transformed signal produced by the signal processor back into a waveform suitable for use as the threshold signal T. The operator may also include or be used in conjunction with an amplifier or a plurality of amplifiers to amplify the signal being processed to produce the variable threshold signal T.

The operator could alternatively be an analogue device giving the appropriate transfer function or an approximation of it.

In the embodiment of the invention where the input to the operator comprises a signal produced by a signal processor and applied to the modulator, the signal processor function of the operator may be provided by the same signal processor.

In any of the above embodiments, where a transfer function is applied by an operator to a monitored signal to produce the threshold signal T, the transfer function may be applied by use of a look up table held in a memory which stores corresponding values of the signal before and after application of the transfer function. The stored corresponding values for the look up table may be calculated from known theory and/or obtained by measurement, e.g. in a training mode. The memory may form part of, or be associated with, the signal processor employed to produce output information applied to the modulator.

Digital signal processors (DSP) which may be pre-programmed to carry out pre-determined mathematical operations as transfer functions on variable input signals are known per se. Examples of such mathematical

operations for use in the context of the present invention are described later.

The operator could alternatively be an analogue device giving the appropriate transfer function or an approximation of it.

The mathematical operation applied by the transfer function operator is one which provides a variable threshold signal T value which when combined or compared with the input RF signal amplitude value a at the RF amplifier causes the RF amplifier to produce an output signal O having an amplitude which, when plotted as a function of the amplitude value a of the input RF signal I, is substantially linear or approximates to linear in at least part of the plot. Preferably, the plot is linear over at least 80%, desirably at least 90% of its range. This is in contrast to conventional class C amplifier configurations which give a highly non-linear plot when operated in a conventional manner.

The amplifying device employed in the circuit according to the first aspect of the invention may comprise an amplifying device arranged in a class C configuration modified so that the input signal I and the threshold signal T are applied together via separate input terminals to be combined at a single electrode of the amplifying device. The amplifying device may comprise a solid state amplifying device such a transistor which may be in bipolar form or in field effect (JFET or MOSFET) form. For example, where a MOSFET (metal oxide semiconductor field effect transistor) is employed, the input signal I and the threshold signal T may be combined at the gate electrode of

the transistor. The output signal O may be extracted from the drain electrode. Where the transistor is in the form of a bipolar junction transistor the input signal I and the threshold signal T may combined at the base of the transistor and the output signal O may be extracted from the collector of the transistor. Bias voltages in each case may be applied as in a usual class C configuration. As mentioned earlier, in one embodiment, the bias voltage e.g. to the emitter in a junction transistor in a class C configuration, may be varied in accordance with the variation in threshold T.

The amplifier circuit according to the first aspect may include two or more amplifying devices. Such devices may be mutually connected in a parallel or a series configuration in a known manner to give a greater output for a given input.

The present invention provides an amplifier circuit which may have a basic configuration similar to that of an RF class C amplifier but which surprisingly and beneficially can provide an amplified output which is a linear function of its input over a substantial part of the output range yet still retain the high efficiency of a class C amplifier. Comparable linearity is only normally obtained with a class A or AB amplifier and the improved linearity provides for amplification of an RF signal a surprisingly good combination of linearity of response and high efficiency. The high operational efficiency leads beneficially to considerably reduced power consumption compared with a class A or AB configuration.

The amplifier circuit according to the present invention may find use in RF circuits for a wide number of

applications particularly digital applications. Such applications include transmitters for RF communications, RF smartcards, RF near field excitation devices, radio and television broadcasting, radar and many others. In this specification, 'RF' is generally understood to mean frequencies of greater than 10KHz, e.g. up to 500GHz. In many cases the RF energy produced in the application will have a frequency of from 100KHz to 100GHz.

According to the present invention in a second aspect there is provided a RF communications transmitter which includes an amplifier circuit according to the first aspect.

Where the invention is employed in RF communications transmitters, such transmitters may be incorporated in communications apparatus. For example, the apparatus may comprise a mobile or fixed radio transceiver. Mobile radio transceivers are also referred to herein as mobile stations (MSs). The term 'mobile station (MS)' is intended to include within its meaning apparatus such as mobile and portable telephones and mobile and portable radios, data communication terminals and the like which operate by radio communication. Systems which provide communications to or from MSs by fixed or base transceivers known in the art as 'base transceiver stations' or 'BTSs' may be arranged to give communications coverage in a network of regions known as cells and are referred to herein as cellular radio communications systems.

Thus, the invention may find partcular use in a MS or in a BTS of a mobile or cellular communications system. The operational power levels are much greater in a BTS than in a MS and the benefits of the invention are therefore

potentially greater in a BTS. For example, in a BTS power amplification stage in which the invention may be employed, the RF signal may be amplified from a power level of typically 1W to one of typically 50W (e.g. from 25W to 75W). The following potential benefits are available in a BTS or a plurality of BTSs used together in a network control installation often referred to as a SwMI (switching an management infrastructure) installation. Higher efficiency which may be obtained in a linear response circuit compared with the prior art provides reduced power consumption which in turn allows smaller operational units to be built. Compared with currently available units, such smaller units can be built more cheaply using less components and operated more reliably at lower operating temperatures with less need for associated cooling and air conditioning arrangements. Floor space occupied at a BTS site and the cost of its rental may also be beneficially reduced.

The MSs and BTSs in which the invention may find use in a mobile or cellular communications system may be units designed to operate according to the TETRA (Terrestrial Trunked Radio) standards. This is a set of operational standards for modern trunked RF communications systems specified by the ETSI (European Telecommunications Standards Institute). In those standards, the communications protocol involves digital information (e.g. voice, data or video information) being contained in phase components of a RF signal modulated using the DQPSK (differential quadrature phase shift keying) system referred to earlier. Signals sent to a BTS from a MS (uplink) and from a BTS to a MS (downlink) are at different

frequencies (FDD or frequency division duplex). Operating frequencies for TETRA systems are narrowband frequency channels which are in several specified frequency ranges including the following: (i) 380MHz-390MHz uplink/390MHz-400MHz downlink; (ii) 410MHz-420MHz uplink/420MHz-430MHz downlink. Each channel used has a bandwidth of 25kHz and can carry 36kbit/sec.

The TETRA modulation protocol is such that the signal amplitude between consecutive digits of information never falls below a minimum level, e.g. approximately 15% of the maximum amplitude, and this is particularly suitable for use of the amplifier circuit according to the invention to amplify such signals. This is because the response of the amplifier circuit can be designed so that amplitudes of input signals to be processed are in a linear response region of the circuit well above any non-linear response region which may apply at very small amplitudes.

If required however, additional linearisers, as known in the art, e.g. for use in conjunction with conventional non-linear class C amplifiers to compensate for non-linarity of the circuit operation, may be employed in conjunction with the amplifier circuit of the present invention to deal with any non-linear response which does occur in part of the response plot in use of the amplifier circuit of the present invention. The output of the amplifier circuit of the present invention may for example provide the input to a Cartesian loop amplifier circuit.

For use in a transceiver (e.g. BTS or MS) to be used in a TETRA communications system, the power amplifier incorporating one or more amplifier circuits according to the invention preferably provides a linear response in an

output signal strength range of at least 70dB, preferably at least 80dB.

Known automatic gain control (AGC) amplifying circuits employ threshold signals. However, the amplifier circuit according to the invention is fundamentally different from such circuits. In an AGC circuit, the object is to adjust the gain so that the output level is the same for different input signal strength levels. In contrast, the circuit of the invention is intended to adjust the threshold so that the gain is the same (or remains similar) for varying input levels of a given signal.

Embodiments of the present invention will now be described by way of example with reference to the accompanying drawings, in which:

BRIEF DESCRIPTION OF THE ACCOMPANYING DRAWINGS

Figure 1 is a schematic representation of a RF threshold power amplifier for use in embodiments of the present invention.

Figure 2 is a graph of input and output amplitude plotted against time for the RF threshold power amplifier shown in Figure 1.

Figure 3 is a graph of amplifier response, namely output amplitude plotted against input amplitude, for different threshold functions used in the RF threshold power amplifier shown in Figure 1.

Figures 4 to 8 are a schematic block circuit diagrams of alternative RF transceivers each including an amplifier circuit embodying the invention employing a RF threshold power amplifier of the kind shown in Figure 1.

Figure 9 is a graph of normalised output as a function of normalised input for a class C power amplifier and also shows the threshold signal T required to provide a linear response when the amplifier is used in a circuit embodying the invention.

DESCRIPTION OF EMBODIMENTS OF THE INVENTION

The invention uses a RF 'threshold PA (power amplifier)' which comprises a new form of high bandwidth (BW) RF amplifier with suitable biasing circuitry. The amplifier has a BW of at least a factor of 5, preferably at least a factor of 10 greater than the operating frequency of the signal which it is amplifying. The threshold PA is defined as a PA whose output O is either 0 (e.g. ground) or 1 (e.g. a voltage defined by the supply voltage used), dependent on the input signal I. If the input signal I is above the level of a given threshold T, the output is 1. If the input is equal to or below the given threshold level T, the output is 0.

Such a threshold amplifier TPA is illustrated in Figure 1. The threshold amplifier TPA has two inputs namely an input signal I to be amplified which is applied to a first input terminal E1, a threshold signal T which is applied to a second input terminal E2 and output signal O produced at a third or output terminal E3. The output signal O for a given input signal I and threshold signal T is as defined above. In practice, the input terminals E1 and E2 may be combined at a common input electrode of an amplifying device within the threshold PA, e.g. the gate of a MOSFET.

The principle of operation of such a threshold PA will now be described and illustrated with reference to Figure 2. The input signal I for the threshold PA is a narrowband signal with both amplitude and phase information of the form:

$$I = A\cos(\omega t+\varphi) \qquad \text{Equation 1}$$

where A represents a peak amplitude, and ω, t and φ represent respectively angular frequency, time and phase.

The output O of the threshold PA will be:

$$O = 1 \text{ if } I > T$$
$$O = 0 \text{ if } I \leq T$$

For narrowband signals the operation of the threshold PA can be analysed assuming that for a given moment in time the values of A and φ are constant. This operation is illustrated in Figure 2. For simplicity, ω can be normalised to 1 and φ can be set to 0 and it can be shown that the output O of the threshold PA is:

$$O = \begin{cases} 1 & \text{for } 0 < t < \alpha \\ 0 & \text{for } \alpha < t < 2\pi - \alpha \\ 1 & \text{for } 2\pi - \alpha < t < 2\pi \end{cases}$$

where t is the phase angle of the signal (or elapsed time) and α is a particular phase angle which is given by:

$\alpha = \arccos(T/A)$ for $A > T$ and $\alpha = 0$ for $T \geq A$.

The threshold T is assumed to be positive (like the peak amplitude A of the input I).

For an input I to the threshold PA which is a sine wave having a peak amplitude A of 1.5 (arbitrary) amplitude units as represented by curve A2 in Figure 2 and a threshold T which is 0.8 amplitude units, the output O of the threshold PA is roughly a rectangular wave as indicated by waveform B2 having a height of approximately 1 amplitude unit as shown in Figure 2.

It can be shown that the width of the output signal pulses in the waveform B2 produced by the threshold PA is proportional to the amplitude of the input I, i.e. the output signal O is pulse width modulated in accordance with the input amplitude variations. In practice, the output O of the threshold PA contains harmonics. Higher harmonics may be filtered away in a known manner by passing the output O through a low pass filter (LPF) so that only the first harmonic remains. It can be shown using Fourier analysis that the amplitude and phase of the first harmonic of the output signal O are given by:

$O_{1st} = 2/\pi \sin(\alpha) \cos(\omega t+\varphi)$, - Equation 2, which may be expressed as:

$$O_{1st} = 2/\pi \sin(\arccos(T/A))\cos(\omega t+\varphi) \qquad \text{- Equation 3}$$

For $A > T$, the threshold PA shows a finite small signal gain. This is a feature that a conventional class C amplifier does not show. This unexpected beneficial

feature allows the threshold PA to be a part of a power amplification system.

By having a fixed level for the value of the threshold T, the threshold PA will be highly non-linear. However, it is possible to adjust the functional relationship between the amplitude of the input signal I and the amplitude of the output signal O. In particular, in accordance with the invention, the threshold T can be dynamically or adaptively adjusted so that the threshold PA produces an output signal O which in at least part of its range has an amplitude which is a linear function of the amplitude of the input signal I. For example, the threshold signal T may be varied in one of the ways described earlier, namely: (i) as a function of the input amplitude by sampling the input amplitude using a feed forward loop arrangement; or (ii) as a function of a signal representing the input amplitude by calculating what the input amplitude will be; or (iii) as a function of the output amplitude by sampling the output amplitude in a feedback loop arrangement, or a combination of these ways, to achieve this linearisation.

A suitable threshold signal T for application to the threshold PA may be obtained by use of an operator applying a transfer function to a suitable input to the operator. This is illustrated further as follows.

Figure 3 illustrates the effect of using different transfer functions to generate the threshold signal T. If the threshold signal T is a constant (0.2 input amplitude units) the highly non-linear curve A3 shown in Figure 3 is obtained for the relationship between input

amplitude and output amplitude. However, if the transfer function is changed to:

$$T = A - (\pi^2/8)A^3 \qquad \text{Equation 4}$$

where Equation 4 is an approximate simplified solution of Equation 3 given earlier to obtain T, the response curve B3 shown in Figure 3 is obtained. Curve B3 has improved linearity compared with curve A3.

If a more precise solution for T is obtained from Equation 3 by using as a transfer function:

$$T = A \cos(\arcsin[A\pi/2]) \qquad \text{Equation 5}$$

then the response obtained is as represented by curve C3 shown in Figure 3 which beneficially is substantially linear over a large part of its range.

Responses such as those illustrated by curves B3 and C3 shown in Figure 3 may be obtained by use of the appropriate transfer function to derive a suitable variable signal as the threshold signal T. The variable signal may be generated by applying in an operator the appropriate transfer function (Equation 4 or Equation 5) to a signal representing the input I, produced either by sampling the input signal I or by calculation from the signal employed for modulation which will result in a given input signal I as described earlier.

Linearity in at least part of the response curve may also be obtained by sampling the output O of the threshold PA and applying in an operator in a feedback loop arrangement one or more transfer functions to the

sampled signal to obtain an appropriate dynamically varying threshold signal T.

For very small input amplitudes, the threshold T may become only marginally smaller than the input signal and the required bandwidth of the threshold PA may become very high as the output O correspondingly becomes a series of only very narrow pulses. However, in practice, a smooth transition to a threshold PA will take place almost automatically in a class C PA implementation as there will not be infinite gain for small signals and also the amplifier will have a limited BW.

Figures 4 to 8 show examples of circuits embodying the invention using the threshold PA which has been described with reference to Figures 1 to 3. The circuits shown in Figures 4 to 8 are various forms of transceiver circuit for use in a MS or a BTS of a radio communications transceiver. Components which in Figures 4 to 8 have the same reference numerals have like functions.

In Figure 4, a transceiver 1a is shown. A carrier frequency generator 3 produces a baseband carrier frequency signal which is applied to a modulator 5. The baseband carrier frequency signal is modulated in the modulator 5 by applying thereto digital data from a DSP (digital signal processor) 7. The modulated output from the modulator 5 is applied to an upconverter 9 which converts the modulated baseband signal to a modulated RF signal. The modulated RF signal is applied as an input signal I to a threshold PA (power amplifier) 11 as described earlier. A sample of the input signal I is fed

to an operator 13 which applies a transfer function to the sampled signal to produce a threshold signal T which is also applied as an input to the threshold PA 11. An amplified output signal O is produced by the threshold PA 11 and is filtered by a LPF (low pass filter) 15 which extracts from the output signal O harmonics other than the first harmonic. The amplified and filtered output signal from the LPF 15 is delivered via a switch 17 to an antenna 19 which transmits the signal over the air as a RF signal to a remote receiver (not shown). Incoming RF signals may be received by the antenna 19 and diverted by the switch 17 to be processed by a receiver 21 in a known manner.

The operator 13 is a device which applies a suitable transfer function to the sampled input signal I in one of the ways described earlier, e.g. using the function defined by Equation 3 or Equation 4, to produce a suitable threshold signal T. The threshold signal T which is produced will have an instantaneous amplitude which is a suitable fraction of the instantaneous amplitude of the input signal I to give an appropriate pulse width in the output signal O as explained earlier with reference to Figure 2. As stated earlier, the operator 13 may include the following components: a signal peak monitor which measures the value of the peak envelope of the input signal I being sampled and a processor. The processor may include an A to D (analogue to digital) converter which digitises the measured values, a digital signal processor which applies the transfer function as a mathematical operation, a D to A (digital to analogue) converter which converts the

digitally transformed signal back into a voltage waveform suitable for use as the threshold signal T and one or more amplifiers to amplify the signal being processed.

The functions of the DSP 7 and at least part of the operator 13 shown in Figure 4, especially the part carrying out the mathematical operation, may in practice be combined in a single processing unit (e.g. a digital microprocessor produced and programmed to operate in a known manner).

Alternatively, the processor of the operator 13 can be an analogue circuit which operates on the peak signal by applying a function which approximates to Equation 5.

In Figure 5 an alternative transceiver 1b is shown. The transceiver 1b operates in a similar manner to the transceiver 1a of Figure 4 except that an operator 21 is used in place of the operator 13. The operator 21 receives an input from the DSP 7. The signal from the DSP 7 contains the digital information employed to produce modulations in the modulator 5. The signal is processed by the operator 21 so as to transform the signal into a corresponding threshold signal T which has an amplitude variation calculated to be proportional to that of the actual input signal I.

In Figure 6 a further alternative transceiver 1c is shown. In this case, the operator 21 is replaced by an operator 25. The operator 25 receives via a feedback loop 27 a sample of the output signal produced by the LPF 15. The operator 25 processes the sampled signal by applying a transfer function thereto which will linearise the response of the threshold PA 11 when the

transformed signal is applied as the variable threshold signal T to the threshold PA 11. In a feedback loop arrangement such as that shown in Figure 6, the time constant of the operator 25 is adjusted to suit the feedback loop dynamics and the bandwidth of the signal being processed in the feedback loop.

In Figure 7 a further alternative transceiver 1d is shown. In this case, the operator 25 is replaced by an operator 29. The operator 29 receives via a feedback loop 31 a sample of the output signal produced by the LPF 15 in a similar manner to the arrangement using the feedback loop 27 in Figure 4. However, in Figure 7 the operator 29 also receives via a further feedback loop 33 an input which comprises a sample of the output of the threshold PA 11 prior to filtering in the LPF 15. The operator 29 processes the sampled signals by applying thereto suitable transfer functions. The processed signals are combined to provide the variable threshold signal T which is applied to the threshold PA 11 to linearise the response of threshold PA 11.

In Figure 8 an alternative transceiver 1d is shown. In this case, the operator 25 (Figure 6) is replaced by an operator 35. The operator 35 receives via a feedback loop 37 a sample of the output signal produced by the LPF 15. The operator 35 also receives as an input signal via a feed forward connection 39 a sample of the input signal I as in the arrangement of Figure 4. The operator 35 processes the sampled signals forming its respective inputs by applying thereto suitable transfer functions. The transformed signals are combined and employed to provide the variable threshold signal T which when

applied to the threshold PA 11 together with the input signal I further linearises the response of the threshold PA 11.

In a further alternative transceiver (not shown) which is a modified form of that shown in Figure 8, the operator employed to produce the threshold signal T may apply a transform function which gives PID (a combination of proportional, integral and derivative) control of the threshold signal T.

Figure 9 gives a further illustration in graphical form of the transfer function required to provide a threshold signal T in a transceiver arrangement as shown in Figure 4 to give a linear response in the operation of an RF power amplifier in class C configuration. Assume that the amplifier ('class C PA') has the conventional response shown as the curve A9 in Figure 9. There will be no output until the amplitude of the input is above 0.1. The level of 0.1 is an arbitrary amplitude level which could for example result from the gate-source voltage drop in a MOSFET with very high gain. It can be seen that curve A9 is highly non-linear. When the normalised input level of $2/\pi$ is reached the maximum output level of the class C PA is achieved.

Assume that the class C PA is used as the threshold PA 11 in an arrangement as shown in Figure 4 and is supplied with a threshold signal T such that the required response curve is linear. The required linear response curve is shown as line B9 in Figure 9. The threshold signal T required to provide this response as a function of the input follows the curve C9. For input levels below 0.1 a negative threshold is required to

offset the input to the class C PA so that overall its input is greater than 0.1 so that the class C PA is still is excited. For input levels above 0.1 the threshold signal T offsets the input signal I to the class C PA less than the peak of the input signal I supplied, thereby reducing the output (curve B9) compared to the output (curve A9) obtained if the threshold signal had not been applied. A transfer function giving the curve C9 can be implemented in one of the ways described earlier.